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RECENT PROGRESS IN ELECTROMAGNETIC ABSORPTION
AND DOSIMETRY IN BIOLOGICAL SYSTEMS

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December 1978

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9 Interim rept.

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14 NAMRL-1261

Naval Medical Research and Development Command
17 ZF51 524 015 0036

16 FS1524

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11 21 December 1978

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406061

SUMMARY PAGE

THE PROBLEM

Dosimetry, as a subset of research in electromagnetic (EM) bioeffects, has made such rapid progress during the last decade that many scientific investigators are unaware of the present state-of-art. As a result, inadequate utilization of available technology is seen in much research currently in progress. Such research, conducted in the absence of sound dosimetry design, lacks credibility. This study provides a usable orientation in present and future dosimetric technology through a documentation of the swift progress in this area since 1969. The information contained in this report can assist researchers in making full use of the latest dosimetric techniques and devices to quantitatively establish the existence of observed effects.

FINDINGS

The rapid pace of research in electromagnetic absorption in biological systems was stimulated by the intent of many workers to develop a quantitative basis for the evaluation of bioeffects. In the United States, close coupling was established and maintained among theoreticians, empiricists, and instrumentation specialists to propel basic knowledge of plane-wave absorption from crude one-dimensional tissue analysis to realistic computer-derived human models. At times theory was leading experiment; while at other times experimental results lead the way. Progress in absorption and dosimetry is still underway, and higher degrees of resolution are needed. The elaborate, man-sized computer models are still rather gross generalizations of the actual human, and many of the current experimental results are based on the use of scaled, simplified models. The problem of near-field exposure is, moreover, just beginning to be addresed. A beneficial side effect of the vigorous activity within the realm of EM dosimetry has been the advent of improved analytical tools such as EM compatible temperature probes and standardized power monitors. These tools can profitably be used by all investigators in studying EM bioeffects and not only by those working in dosimetry.

RECOMMENDATIONS

The operational environment of Navy combat platforms is one of limited space crowded with apparatus and personnel. Obviously, a compromise must be achieved as to the exposure of personnel to an entire spectrum of potential biophysical agents, one of which is electromagnetic (EM) radiation. The biological effects of such radiation are not all well established, but they are beginning to yield to systematic laboratory analysis. The correlation of these recognized effects to safety hazards in the operational environment depends principally on detailed dosimetric analysis of the laboratory research and of the onboard environment. The study of EM absorption and dosimetry in man therefore serves a vital function in the evaluation of stresses in and hazards to Navy personnel. It is recommended that a strong program of dosimetry be maintained within the Navy to determine the locus and level of electromagnetic absorption in all personnel who must function in proximity to radiating equipment under operational conditions. Such a program would not only contribute to the advancement of knowledge in dosimetry but also provide a quantitative basis for the decision of human safety versus platform effectiveness for EM radiation environments.

INTRODUCTION

Research in electromagnetic (EM) bioeffects is truly an interdisciplinary, multidisciplinary field touching a wide spectrum of professions from engineering to medicine. A typical listing of EM-induced effects includes central nervous system (CNS), developmental, physiological, behavioral, and therapeutic effects; however, one of the fastest developing segments of the total effort is that of EM dosimetry and absorption. The growth of this subset of investigation is clearly seen in the comparison of the number of papers (3) that addressed these questions in the Proceedings of the 1969 Richmond Symposium with the number of such presentations (17) given at the 1977 International Symposium at Airlie, VA. The present report describes progress since 1969 in the quantitative study of whole-body absorption of electromagnetic energy. Also discussed is the current state-of-art in dosimetry as well as some unanswered questions.

In the organization of this report, four major topics are considered under each of four discrete time frames. The four major topics to be considered within each period are: 1) philosophical directives or overviews given typically as a symposium introductory presentation, a panel discussion, or otherwise published in the open literature; 2) theoretical results that represent progress in EM absorption and dosimetry; 3) experimental absorption and dosimetric results; and 4) instrumentation, either developed or made available, with special usefulness in advancing the state-of-art. Emphasis is given to studies that have dealt with whole-body absorption of EM energy in free-field conditions or in simulated free-field conditions. Special attention is also given to the phenomenon of EM resonance absorption in man and other biological systems. Discussion has been limited to significant or representative examples of progress in this field. For example, not all of the many analyses of EM absorption in a spherical model are cited nor are all of the various temperature probes mentioned.

The time frames correspond to certain landmarks such as major symposia on EM bioeffects. They are; 1) 1969-73 which includes the Symposium on Biological Effects and Health Implications of Microwave Radiation held in Richmond, Virginia, the 1971 IEEE Transactions on Microwave Theory and Techniques, Special Issue on Biological Effects of Microwaves, and the International Symposium on the Biologic Effects and Health Hazards of Microwave Radiation held in Warsaw, Poland; 2) 1974-75 which includes the Conference on Biologic Effects of Nonionizing Radiation held in New York and the 1975 Annual USNC/URSI meeting held in Boulder, Colorado; 3) 1976-77 which includes the 1976 Annual USNC/URSI meeting held in Amherst, Massachusetts, and the 1977 International Symposium on the Biological Effects of Electromagnetic Waves held in Airlie, Virginia; and 4) 1978 and beyond, within which two recently concluded symposia are discussed, the 1978 Symposium on Electromagnetic Fields in Biological Systems held in Ottawa, Canada, and the Open Symposium on the Biological Effects of Electromagnetic Waves held in Helsinki, Finland. To preserve coherence in chronology, results initially presented at one of the major listed symposia will be included in the time frame containing the symposium and not in the time frame during which the proceedings or other publication became available.

It will be shown that considerable progress has been made since 1969 in EM dosimetric knowledge through improved experimental techniques and tools, through systematic theoretical analyses, and in the adoption of a consistent set of units of measure. This progress has fostered increased dosimetry in the description of nearly all other types of bioeffects research such that the entire discipline is, for the most part, unified in terms of investigators providing either measured data or at least an approximation of the absorbed radiation as one of the independent variables.

TIME FRAME 1969 - 1973

In this time period, there was a great reawakening in the area of electromagnetic (specifically microwave) biological effects. A number of years had passed since the last Tri-Service Program conference (62, 67); public and governmental concern was growing with regard to the health hazards of nonionizing radiation, particularly in light of the disparity between the U.S. and Russian exposure standard (10 mW/cm^2 and 10 $\mu W/cm^2$, respectively) and in reaction to Soviet and Eastern European research reports which were in disagreement with conclusions of the Tri-Service Program. In essence, the time was ripe for a vigorous pursuit of a comprehensive program in this area.

PHILOSOPHICAL OVERVIEW

At the time of the Richmond Symposium in 1969, a general tone of uncertainty was evident in the remarks of a number of participants (19, 27). Results from the Soviet literature indicating bioeffects of electromagnetic radiation (EMR) at thermally insignificant levels were pondered and were considered to be sufficient evidence to warrant further work in this country. The demarcation between thermal effects and nonthermal effects was discussed from a number of viewpoints as were the possible cumulative effects of nonionizing radiation, but no solid consensus existed among the participants along these lines, and an obvious void existed between the requirements of administering the newly enacted Radiation Control for Health and Safety Act of 1968 and the quantitative scientific knowledge needed to support those requirements.

Fortunately, an attitude of cooperation in an international sense was nurtured by mutual efforts by both Western and Eastern scientists to resolve certain disparities that existed in philosophy, methodologies, and results. A monument to this program of mutual cooperation was the 1973 Warsaw Symposium attended by scientists from twelve nations. In the published proceedings of this symposium are listed a number of conclusions and recommendations that reflect a representative cross-section of the philosophy of EM bioeffects as it existed in 1973 (4). Among the recommendations emanating from the Warsaw Symposium were calls for more international coordination of research on the biologic effects of microwave radiation and a call for further studies into such areas as low-level and cumulative effects, cellular effects, and dosimetric, spatial analysis of EM absorption. By the end of 1973, it was apparent that some of the barriers to international cooperation in bioeffects, specifically those separating the Eastern and Western countries, were being broken down.

THEORETICAL RESULTS

At the end of the 1960's the theoretical predictions of EM absorption by biological systems was limited to a simple slab model and the absorption cross-section studies of Anne (3) who used Mie's (63) solution for EM scattering by a sphere. These theoretical bases were inadequate in several areas. For instance, the slab model of a biological system predicted only a simplistic surface absorption that was deemed biologically unimportant for frequencies above 3000 MHz (71), and the scattering cross-section analysis did not explicitly quantify the total average energy absorption of the spherical model. It was soon to be theoretically shown for curved bodies with physiological properties that the internal EM absorption for certain wavelengths was much higher than that predicted by the simple slab model (46).

In later studies of the overall average energy absorption by the physiological sphere, a broad, frequency dependent, absorption peak was predicted by the Mie solution (65). A study of a head-sized spherical model showed internal concentrations of absorbed energy (72), and many theoretical and experimental studies of the head absorption problem were initiated after these results were published. One important early result in theoretical dosimetry was by Lin and coworkers who studied a spherical model of man irradiated by a plane wave (57). Although man is obviously not a physiological sphere, this study was the first to extrapolate overall absorption values to a man model for frequencies between 1 and 20 MHz. Notwithstanding the limitations in frequency and in the assumed model, that paper (57) served as the starting point for many extrapolation studies.

EXPERIMENTAL RESULTS

Very few experimental dosimetric results existed before 1969, and the state-of-art in this area was rather crude at the time of the Richmond Symposium. The uneven nature of microwave-induced heating was studied by Pozos and coworkers, using water or water-based loads and mercury thermometers (69). Baille et al. used a mechanically driven thermocouple needle to plot the microwave dissipation within a dog's eye and within various eye models (9). A notable early experiment was performed by Justesen and King (53). the average whole-body temperature rise of various phantom models was used to quantify the "absorbed dose" of microwave energy. All investigators were eventually urged to incorporate some description of the "absorbed dose" first proposed and used by Justesen and King.

Later, another powerful tool, the thermographic imaging system, was introduced into the area of EM dosimetry. Guy used this method to study the energy distribution in tissue-equivalent phantom materials (38). These artificial tissues simulated living material in terms of electrical properties for the range of frequency being considered, and use of the thermographic imaging system permitted the simultaneous two-dimensional analysis of the amount and distribution of the absorbed microwave energy. This initial publication by Guy and a companion paper by Ho, Guy, and others clearly showed the differential heating patterns caused by different wavelengths and by various microwave applicators for simulated fat/muscle configurations

(38, 43). In a later, very comprehensive, paper by Johnson and Guy (46), the initial thermographic results were reviewed, and thermographic evidence was used to show undesirable features of using metallic electrodes in irradiated preparations. The presence of such metal electrodes was seen to cause large amounts of heating in nearby tissue. Introduction of relatively simple phantom materials and use of thermograms were major advancements in experimental dosimetry, and a rapid development of this field followed.

INSTRUMENTATION DEVELOPMENT

The development of measuring equipment particularly suited for EM bioeffects studies was under way before 1969. Carpuchettes discussed several microwave leakage measuring devices at the 1969 Richmond Symposium (28). Wacker (75) and Bowman 915) presented studies of the theoretical and practical aspects of measuring hazardous microwave fields (76). The Narda 8100 series electromagnetic radiation survey meter was introduced by Aslan in 1970, and this instrument is still in use today typically as a microwave leakage detector (5, 6). A Narda broadband, isotropic power monitor useful from 0.3 to 18 GHz was introudced by Aslan in 1972 (7). Another isotropic microwave power density meter developed at the National Bureau of Standards (NBS) was described by Bowman in 1973 (16). Unlike the commercially available Narda probes, the NBS units were produced on a very small scale with limited availability. The early development of these probes in the United States permitted a high degree of standardization in the incident field parameters of subsequent EM bioeffects studies.

SUMMARY

This period (1969-1973) was a time of consolidation of thought in the United States concerning EM hazards and it was a time when a considerable amount of groundwork was achieved in absorption and dosimetry. These initial accomplishments paved the way for a more rapid rate of progress in this area.

TIME FRAME 1974 - 1975

During this time interval of only two years, the volume of research on the biologic effects of nonionizing radiation was substantially larger than that undertaken during the previous time frame of 5 years. Two major meetings on the topic were held in the United States during 1974 and 1975; they were sponsored by the New York Academy of Sciences and by the United States National Committee of the International Union of Radio Science, respectively. Certain amounts of structure and of differentiation in the overall field of electromagnetic bioeffects evolved during these years. Typically, experimental work became classified under such categories as behavioral, sensory, and developmental; moreover, EM dosimetry was also elevated to the status of a major subdivision of the field. The two conferences had a total of twenty-two presentations on dosimetry that were eventually published, and many of the citations to be listed in this section are to be found in the publications resulting from these conferences.

PHILOSOPHICAL OVERVIEW

The general philosophy presented during this period concerned admonitions to continue the good work already started and established the importance of dosimetric analysis in all EM bioeffects experiments (50). Tyler acknowledged the progress in the area of electromagnetic field measurements and stated that "the prospects for nonionizing radiation research were never more promising . . . ." (74). Guy stressed the need to establish a quantitative data base for the evaluation of EM hazards. He also listed the standardization of techniques for free-space E-and H-field measurements and for absorbed power density determinations in tissue as high-priority items (39).

The increasing emphasis on dosimetric analysis was seen in several papers published in 1975. Johnson stated that all bioeffects studies should include either direct measurements of the EM absorption of a subject or complete information as to the external field configuration such that the internal EM absorption could be approximated using extrapolation techniques that were (and still are) being developed (48). Precision in dosimetric terminology and agreement on usage became a subject of lively interest. Such terms as "absorbed power density," "absorbed energy dose," or "microwave dose rate" were gradually replaced by specific absorption rate (SAR) in watts per kilogram as the accepted parameter of EM absorption (40, 54, 73). Use of specific absorption rate is fraught with several problems, as pointed out by Justesen; nevertheless, its use is, by now, nearly universal.

THEORETICAL RESULTS

During this period, theoretical work under the heading of absorption and dosimetry can be classified into three categories: 1) analysis using standard shapes such as spheres and cylinders, 2) analysis of the prolate spheroid, and 3) analysis of a more-or-less human shaped model. Representative papers of theoretical work using the spherical model include one by Weil (77) analyzing a multilayered sphere and another by Kritikos and Schwan (56) depicting the heating potential in lossy spheres. Theoretical analysis of an irradiated, layered cylindrical model with irregular cross-section was given by Ho (44). Theoretical dosimetry using the prolate spheroid model was initiated at the University of Utah. The Utah model represented an improvement over spherical models, but the mathematical techniques involved in prolate spheroid analysis limited the frequency range to wavelengths that were long as compared to the size of the irradiated model. For the man-sized model, the highest frequency for which the results were valid was about 30 MHz (29, 49). The studies clearly showed that both orientation and frequency were major factors of EM absorption in this frequency range. The total average absorption in the man-sized model was seen to rise sharply with frequency and was highest when the long axis of the spheroid was parallel to the incident electric field. Previous Mie solutions of spherical models had shown a similar frequency dependence at long wavelengths; moreover, the Mie theory predicted the existence of a frequency of maximum average absorption by the physiological sphere (46). This so-called resonant frequency of absorption was being observed experimentally in various laboratories (see next section); therefore, a more refined mathematical technique called "the extended boundary condition method" (EBCM) was used at the University of Utah to theoretically show the existence of such a peak in the prolate spheroid model (10). Because of several weaknesses in the initial EBCM solutions, only a qualitative correspondence could be applied to the man-sized spheroid as to SAR at resonance, but the validity of the prolate spheroid model became firmly established in terms of extrapolation to actual animals such as man, primates, and rodents.

Work from Michigan State University was presented in 1975 showing absorption in a simple block model of man irradiated by a plane wave (21). The tensor integral equation method was used to show EM absorption for frequencies up to 500 MHz. The usefulness of the initial block model of man was rather limited, but a resonant absorption frequency was observed for the model at approximately the same place that the EBCM predicted resonance.

By the end of 1975, emphasis was noticably shifting toward the study of man-related models and away from analyses of isolated spheres and cylinders. Theoretical dosimetry, in a short time, had become an important part of bioeffects research, and the practice of extrapolating absorption parameters from a given model to an actual living system is still widespread.

EXPERIMENTAL RESULTS

In early 1974, experimental dosimetry was trailing theoretical work, but the order was reversed by the end of 1975. The effects of orientation and frequency on EM absorption were first observed in rats and rat models where alignment of the rat's long axis with the incident electric field (E-orientation) showed the strongest average absorption for certain frequencies. Phillips and coworkers found differences in absorption based on the type of system used, either cavity irradiation or free-space irradiation (68).

Gandhi's initial publication on orientation and absorption gave the power absorbed versus frequency for three orthogonal orientations of the subject in a stripline irradiation system (33). A peak EM absorption for E-orientation was seen at a wavelength of approximately twice that of the subject's long axis. Absorption peaks were also seen for the other two orientations (H-orientation and K-orientation), but the magnitude of these peaks was only about a tenth of that for E-orientation. These lower peaks both occurred at higher frequencies than those observed for the E-orientation absorption peak. Although Gandhi's initial paper dealt exclusively with rats and rat models and although its major results were of a qualitative nature, the contribution represented a significant advance in the understanding of EM absorption in whole-body systems. From that paper (33), valuable information could be directly applied to the EM hazard problem such as the worst-case frequency and orientation for human exposure.

In a series of later papers, Gandhi and coworkers presented more experimental evidence regarding the nature of resonance EM absorption in man and animals (34 - 36). It was shown that the worst-case resonant absorption frequency for the average human was about 70 MHz in the absence of ground-plane effects. For a grounded subject, the resonant frequency was half the original value. Average worst-case absorption for a 10 mW/cm^2 incident power density was determined to be slightly over 2 W/kg for the average person. A disturbing feature in Gandhi's data was the very high neck heating observed in the figurine models. A specific absorption rate of 60 W/kg was predicted for the neck in a full-sized human at resonance with a 10 mW/cm^2 incident level. For the grounded worst-case situation, the ankle regions were the regions of strongest absorption (15-17 W/kg at 10 mW/cm^2).

Prior to this time, experimental dosimetric work had been started by the Air Force at the School of Aerospace Medicine, Brooks Air Force Base, Texas. Some of the initial results were reported at the New York Academy of Science meeting (1). A notable early contribution was seen in a paper by Allen and coworkers (2) in which they presented experimental verification of the theoretical work with a prolate spheroid. They used a large parallel-plate transmission system capable of irradiating live monkey subjects at frequencies up to 50 MHz. It was experimentally deduced that changing the shoulder orientation of the monkeys (either side-to-side or front-to-back with respect to wave propagation) produced significant differences in average absorption. This deduction caused some emphasis to be removed from the prolate spheroid model and placed on an ellipsoidal model of man for more realistic theoretical results. In this instance, experimental results were leading the way for theoretical work.

Most of the results mentioned in this section were to be modified to some extent in ensuing years, but the basic features of the human-related absorption parameters established during this time frame are intact today. Although the initial indications of neck heating appear to have been too high, total absorption for an average person in worst-case free-field conditions at approximately 80 MHz is still estimated to be between 2 and 3 W/kg at 10 mW/cm^2.

INSTRUMENTATION DEVELOPMENT

Three notable developments in instrumentation surfaced during the years of 1974 and 1975. First, a temperature probe usable in a microwave environment was developed at the University of Utah (47, 58, 70). This device consisted of a liquid crystal sensor combined with an optical fiber communication link such that no conductive material was incorporated into the measuring element. Prototypes of this temperature probe were used in several laboratories throughout the United States with relatively good success, and the device is now commercially available. Another instrument using an optical transmission link was a miniature, isotropic field probe developed during this period at the Bureau of Radiological Health (12, 24). The first version of the probe was usable from about 1 to 10 gigahertz and could be implanted in either real or simulated tissue to measure internal fields. While initially very promising, the probes, unfortunately, have not been fabricated in a quantity to make them commercially available at this time. Modifications and improvements to the basic design of the device have been made, and work is under way to attempt commercial production. A third instrumentation development came from Narda in the form of an isotropic, low-frequency, H-field radiation monitor with an orthogonal loop array that was useful from 10 to 300 MHz (8).

SUMMARY

It is easily inferred from looking at the advances in knowledge of just the dosimetric aspects of EM bioeffects research that great strides had been made during these two years (1974-1975). The art had progressed from knowledge of only spherical absorption to a knowledge of the basic features of EM absorption in man. A major task remained in getting others in the field to utilize the dosimetric tools that had been provided and to standardize the use of dosimetry in other types of irradiation experiments.

TIME FRAME 1976 - 1977

During these years, the study of electromagnetic bioeffects grew to be a significant branch of scientific endeavor as shown at two major scientific meetings. First was the 1976 Annual Meeting of USNC/URSI, which convened October 11-15 in Amherst on the campus of the University of Massachusetts. Second was the 1977 International Symposium on the Biological Effects of Electromagnetic Waves, which was held October 30-November 4 at Airlie, Virginia. The schedules of both of these meetings were full, and the attendance was heavy; more than three hundred persons attended the Airlie Symposium. More coorperation appeared to be evident between East and West during this period. American scientists in EM bioeffects visited Soviet research laboratories, and a number of Russian and East European scientists attended the 1977 symposium.

PHILOSOPHICAL OVERVIEW

As viewed by leaders in the field, the area or EM bioeffects was advancing steadily, but it was feared that continued support of research might not be maintained by various agencies of the U.S. Government (55). These leaders pointed with pride to accomplishments of recent years in EM dosimetry, therapeutic hyperthermia, and in greater understanding of the microwave-hearing effect. In his keynote address to the 1977 International Bioeffects Symposium, C.C. Johnson listed many of the contributions in this area attained through interdisciplinary and international cooperation (51). Unfortunately, the scientific community was to lose the guiding force of C.C. Johnson soon after the 1977 meeting, for he was stricken with cancer and died early in 1978.

A new feature with respect to the study of EM bioeffects was developing during this period. It was the publication of information on EM bioeffects by journalists in the news media and popular press (18). Public policy makers became concerned, and research data, especially results indicating effects, were given a high degree of public visibility. Some researchers were asked to interpret scientific data and to provide conclusions that could be readily understood by the public. This forced attempt to prematurely draw broad conclusions from inadequate data led to differing opinions from reputable scientists and to some polarization among researchers. It was obvious that much of this public debate could have been prevented if all the published biological experiments had been done with adequate dosimetry, and this fact provided a stimulus in theoretical and experimental dosimetry to develop practical methods and experimental guidelines that could be readily applied by all scientists to enhance the validity of their results.

THEORETICAL RESULTS

Expansions of knowledge in theoretical EM absorption and dosimetry continued unabated during this period. The initial work in calculating absorption in a prolate spheroid biological model for long wavelengths was expanded into a handbook which was widely distributed (45, 52). The handbook gave the whole-body average SAR to be expected in many models, ranging from insect shape to man, for frequencies below resonance. Long-wavelength theoretical solutions were also found for EM absorption in an ellipsoidal model of man (59 - 61), and progress was reported in using the extended boundary condition method (EBCM) to predict absorption in spheroidal models at frequencies of resonance absorption (11).

Theoretical studies of EM absorption in realistic man models also showed significant progress. The original block model of a man used by Chen and coworkers at Michigan State University (20, 21, 23) was made more realistic, and the published results (22) showed a good correspondence to experimental dosimetry results obtained primarily in Gandhi's laboratory. Also during this time, theoretical work on a realistic man model was started at the University of Utah. The moment method of analysis was used on a highly realistic model, and an initial report (42) showed consistency with experimental results, with the dosimetry handbook (45), and with Chen's work (22).

During this period, the theoretical study of EM absorption and dosimetry, for the most part, caught up with the progress that experimental studies had brought. Probably the most significant development was the introduction of the Radiofrequency Radiation Dosimetry Handbook (45). Even though this first edition was rather limited in the spectrum of frequencies used, the handbook represented a needed first step in unifying and solidifying the use of dosimetric analysis in all EM bioeffects experiments.

EXPERIMENTAL RESULTS

In 1976 and 1977, the number of contributions in experimental EM dosimetry was not as large as during the previous two years. Important results were obtained, yet the overall volume of activity seemed to decline. Gandhi and coworkers pursued the study of absorption in animals and in figurine models of man to show how the presence of ground planes and reflectors affected the overall absorption picture (37). Gandhi's data showed that considerable enhancement in EM absorption takes place when the subject is either conductively grounded or is in the vicinity of large, conducting reflectors. This enhancement of absorption over the free-space situation ranged from a factor of two for a simple grounded subject to a factor of more than ten for a subject located near a corner reflector.

Chou and Guy used a cavity irradiation system and a thermographic camera to show absorption patterns in scaled models of man for frequencies above resonance (25). At 138 MHz specific absorption rates as high as 18 W/kg were shown to occur in localized regions of the body for exposures at 10 mW/cm^2. The neck, ankles, and wrists were seen to be areas of high absorption at 198 MHz. At frequencies above resonance, the total average SAR was reduced, but their data showed localized resonances at frequencies above whole-body resonance.

At the 1977 international bioeffects symposium, Olsen presented dosimetric results obtained in a full-sized phantom model of a man (65). In this full-sized model irradiated in the far zone at 1.29 GHz, absorption was shown to be essentially a front-surface effect. The average total absorption calculated for the man-phantom was 0.31 W/kg for 10 mW/cm^2, and this value agreed well with theoretical predictions presented at the same symposium.

Perhaps the single most important contribution of experimental dosimetry during this period was the finding of localized resonances in various parts of the body where the thermal burden of irradiation could be dangerous even at 10 mW/cm^2 incident intensities. These findings prompted the serious consideration of the 10 mW/cm^2 safety standard by scientists in this area, especially those who were also members of the American National Standards Institute (ANSI) committee charged with the evaluation of the validity of that safety standard.

INSTRUMENTATION DEVELOPED

The development of instrumentation specifically designed for use in the irradiation of biological systems or models continued at a rapid pace in 1976 and 1977. The miniature implantable field probe, previously noted, was further developed (13). Bowman reported the development of a unique temperature probe that had conductive yet highly resistive leads (17). By the end of 1977, it was announced that this temperature probe was commercially available.

Other temperature probes were presented at the 1977 international symposium. Among these were a gallium arsinide/optical fiber device introduced by Christensen (26), and an inexpensive nonmetallic thermocouple probe described by Olsen and Molina (64). Deficis and Priou also introduced a nonperturbing temperature probe in 1977, based on optical reflection from a volume of dielectric material (31).

Progress was made in other areas using existing technology. Accurate whole-body absorption measurements were reported by Blackman and Black using a Dewar-flask calorimeter (14); twin-well and gradient-layer calorimeters were also used in this application. A nonmetallic electrode system for recording EEG and ECG was introduced by Flanigan and coworkers (32). The various types and sources of instrumentation developed during this period show that much effort was being expended to place EM bioeffects research on a firm quantitative basis with respect to the amount of absorbed energy used in experiments.

SUMMARY

The advances in EM bioeffects dosimetry during this period (1976 - 1977) provided much of the technological groundwork on which to build a quantitative data base that any investigator could easily use. This progress was very timely considering the rise of public scrutiny in the field that demande careful attention to research design and methods.

TIME FRAME 1978 and BEYOND

Progress in the dosimetry of irradiated biological systems is steadily advancing. Dosimetric tools available today are much more sophisticated than they were five years ago, and there is reason to expect that future progress in the area will outstrip that seen since 1969. Two major symposia in EM bioeffects were held during 1978; the first was the 1978 Symposium on Electromagnetic Fields in Biological Systems held in Ottawa, Canada on June 27-30, and the second meeting was the Open Symposium on the Biological Effects of Electromagnetic Waves held at the XIX General Assembly of the International Union of Radio Science in Helsinki, Finland on August 1-8. Much of the material to be presented in this section concerning the current status and future direction of research in EM absorption and dosimetry was obtained directly from the participants of these two symposia

PHILOSOPHICAL OVERVIEW AND OUTLOOK

A new society was formed in 1978 to meet the needs of the expanding area of EM bioeffects research. The new group called itself The Bioelectromagnetics Society, and initial response to it has been positive. One function of the new society will obviously be the orderly dispensation of philosophical guidance to organize, unify, and stimulate progress in the area.

Of growing interest at this time is the validity of the 10 mW/cm^2 safety standard at or near the whole-body resonant frequency for man. Another evaluation of the safety standard by ANSI is to be completed in 1979, and the dosimetric results obtained over the past few years will play an important role in this process.

THEORETICAL RESULTS AND EXPECTATIONS

The second edition of the Radiofrequency Radiation Dosimetry Handbook was available by the time of the Ottawa symposium (30). The new edition is much more comprehensive than the original handbook. It covers frequencies up to 100 GHz for most prolate spheroid models. Also given are data regarding metabolic rates of man and animals along with heat-response calculations. An empirical formula is presented along with instructions as to its use that allows calculation of the average EM absorption for biological models of given semimajor and semiminor axes dimensions. It is expected that large use will be made of the revised dosimetry handbook. The future direction of the handbook project is towards the study of near-field conditions.

Theoretical techniques for calculating EM absorption in realistic man models have been undergoing modification. Whereas past studies have discrete blocks in the models, limitations in computing hardware have redirected future work toward using solids of revolution or horizontal slab/slice models for higher frequency analysis. Work in this area should produce results of theoretical man-model absorption of up to 2450 MHz in the near future.

EXPERIMENTAL RESULTS AND EXPECTATIONS

Experimental work currently under way considers such things as measured effects of head resonance in the rat and some discrepancies with the prolate spheroid analysis. Measurements indicate an overall average SAR of 3.6 W/kg at 10 mW/cm^2 at the resonant absorption frequency (41); whereas, the current handbook (30) values show less than 3 W/kg for a similar prolate spheroid. Yet another consideration with respect to the hazards of absorption is that measurements have been made in small, homogeneous models that do not incorporate any internal structures. It could be that the presence of bones or of other tissue structures within the actual man would produce more exaggerated constrictions in reality than are now modeled. It is known that constrictions in cross-section tend to produce areas of high EM absorption, and a worst-case condition might exist that has not been appropriately modeled yet. For reasons such as these, future studies of the full-sized man model at the Naval Aerospace Medical Research Laboratory will incorporate simulated bones within the model in order to model EM absorption as closely as possible, especially in the areas of known hot spots.

In the area of EM absorption thermography, the resolution and quality of obtainable data are increasing. It is currently possible to show the EM-induced heating of such small structures as an insect's leg (66); in the future more magnification will become available such that small, irradiated blood vessels can be thermally imaged <u>in vivo</u>, and perhaps single living cells can be resolved. Microscopic, thermographic analysis is needed in support of tumor-hyperthermia studies and of interaction mechanism research. Much of the EM absorption work being conducted now on the macroscopic whole-body scale will be conducted on the microscopic scale when the measurement tools are sufficiently refined.

INSTRUMENTATION AVAILABILITY, NOW AND PROJECTED

There are currently available to researchers a wide variety of dosimetric instruments with which to pursue quantitative analysis. For whole-body absorption measurements there are now gradient layer calorimeters as well as Dewar-flask units. At least two nonperturbing temperature probes, the liquid crystal optical fiber probe and the four-lead high resistance device, are commercially available. Narda Microwave Company recently introduced an isotropic, broadband power monitor usable to 26 GHz.

Slated for commercial production, but not yet widely available, are the miniature, 3-axis, implantable field probe developed at the Bureau of Radiological Health and the tiny semiconductor/optic fiber temperature probe developed at the University of Utah. Other new devices and/or techniques are in various stages of planning or development such that the horizon is full of prospective instruments. As long as strong emphasis is maintained on the acquisition of quantitative data for all EM bioeffects studies, the development of more and better instruments will be assured.

CONCLUSIONS/RECOMMENDATIONS

Since 1969, steady progress in EM dosimetry has been accomplished in many areas. In the review of literature it was repeatedly seen that philosophy, theory, experiment, and apparatus were closely coupled. The rapid expansion of knowledge in this area is a tribute to the system of communication and cooperation that has evolved in bioeffects research. Dosimetry and the knowledge of EM absorption have advanced principally because of the emphasis that was placed on the quantitative aspects of experimental results.

Much still remains to be studied in this field, for most of the tabulated dosimetric results are still given in generalized terms, such as "total average SAR" for a given situation or in other terms like "neck SAR" and "ankle SAR." Terms such as these are of only limited usefulness because "total average SAR" gives no information as to possible concentrations of energy deposition in the body, and "neck SAR" gives no information as to possible concentrations of absorption in the various tissues comprising the neck. It is seen that a much higher resolution of the absorption picture is needed to adequately quantify the absorption of irradiation. To provide the improved resolution, realistic adult and child sized models should be used in large transmission systems or in irradiation chambers. The phantoms should incorporate many different tissues and structures, possibly including muscle, fat, bone, internal organs, and cavities. Dosimetric data for frequencies of whole body resonance and higher should be obtained from a number of locations throughout known regions of high EM absorption (36). The number of locations measured should be such that intervals no larger than one-half of the tissue wavelength are maintained throughout the three-dimensional region of interest.

The conditions that have been shown to significantly increase EM absorption should be closely studied. Conducting ground planes and certain reflector plates are quite common in practical situations, and high-resolution dosimetric data should be obtained using grounded models and using reflector-type irradiation systems.

As the use of electromagnetic energy continues to grow in such areas as electronic warfare, cancer therapy, the solar power satellite, etc., our knowledge of the biological effects of nonionizing radiation must also grow to provide a sound rationale for enviornmental and personal protection and to simultaneously utilize such radiation to its maximum possible benefit. The outlook for future benefits based on expanded knowledge is bright. The rate of future successes, however, depends upon the continued high-level of communication and cooperation that has been established.

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1. REPORT NUMBER NAMRL 1261	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) RECENT PROGRESS IN ELECTROMAGNETIC ABSORPTION AND DOSIMETRY IN BIOLOGICAL SYSTEMS		5. TYPE OF REPORT & PERIOD COVERED Interim
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Richard G. Olsen		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Aerospace Medical Research Laboratory Naval Air Station Pensacola, Florida 32508		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS ZF51.524.015-0036
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Medical Research and Development Command National Naval Medical Center Bethesda, MD 20014		12. REPORT DATE 21 December 1978
		13. NUMBER OF PAGES 25
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Microwaves Electromagnetic Radiation Dosimetry		

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report documents the development of electromagnetic (nonionizing) dosimetry since 1969. Insight is provided as to the current capability and limitations of dosimetric technology; future trends in research are also noted. Emphasis on the establishment of a quantitative data base for the evaluation of electromagnetic bioeffects has been a major factor in the rapid progress in dosimetry in the past decade. Recommendations are given for the continued Navy support of research in electromagnetic dosimetry.

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